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Magnetic NDT Technology for Characterizing Materials – A State of the Art Survey

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Abstract

Per definition, magnetic NDT can be applied at ferromagnetic material only. However, most of the materials we use today still are iron-based steels with bcc lattice and therefore magnetic. The magnetic properties of these materials can be utilized in NDT for defect detection and sizing as well as for materials characterization in terms of mechanical properties determination, also in on-line process-controlled systems.

MT is old and one of the most applied NDT techniques in the world for detecting surface-breaking cracks by using magnetic particles. Nowadays the technique can be mechanized and the interpretation of powder indications as findings is performed by intelligent pattern recognition software, i.e. the drawback to be working with a high human factor influence can be eliminated. However, in complex shaped geometries, for instance pusher beams of steering gears in car industry, the existence of pseudoindications prevent the application of MPI. Based on new magnetic sensors, i.e. GMR, an automatic detection with high sensitivity became possible. Manufacturers in automotive industry after validation of the new technology ask for a replacement of MPI.

There are many similarities between mechanical and magnetic properties of magnetic materials. Microstructure characteristics like vacancies, dissolved atoms, dislocations, precipitates, and grain and phase boundaries influence the dislocation movement under mechanical loads similar as they hinder the Bloch wall movement under magnetic loads. Therefore micro-magnetic techniques are suitable to characterize properties like hardness, yield and tensile strength but also toughness properties like Charpy energy or ductile – brittle transition temperature. The contribution introduces into recently developed industrial applications in steel industry to non-destructively and on-line characterize mechanical properties in the manufacturing process as well as to approaches to describe the ageing state of steels in power plant applications performing an in-service inspection.

Keywords: *Magnetic testing, MPI, Magnetic probes, Materials characterization, Process control, Mechanical properties determination, Ageing phenomena*

1. Introduction

It is now 24 years ago when the author of the paper has taken over the chairmanship "Magnetic Leakage Flux Testing of Welds" which was chaired before by Arie de Sterke, RTD, a pioneer in NDT in the Netherlands. The activity of the working party was on the compiling of a "Manual on Magnetic Leakage Flux Testing" which was proposed for publication by IIW in 1987 [1] and published by TWI in 1988 as IIW handbook

[2]. Everybody of the colleagues engaged in those times was convinced: The technique was matured for a wide application. Besides some scientifically open questions (“How to solve the inverse problem, i.e., how to determine the defect geometry from measured leakage field data?), the main influence variables were known.

The question mentioned above has never played an essential role in practice, because most of the users have applied magnetic leakage flux testing as MPI, of which the indications – at that time – were evaluated by inspectors by eye only and were always influenced by human factors. However, the technique was and still is high sensitive for surface-breaking crack detection.

In the case of automatic magnetic probe inspections, for instance in steel industry for rods and pipes, calibration and acceptance criteria were following threshold criteria according to sensitivity classes. A defect reconstruction using measured amplitude-versus-locus data was not asked for, even if scientist published mathematically sophisticated approaches [3, 4].

However, the drawback in MPI, the strong human factor influence was frankly discussed and first research was stimulated in the direction of automation and pattern recognition.

In 1978 the institute of the author started with first studies, to use micromagnetic NDT techniques in order to characterize relevant microstructure changes in steel. Because the nuclear technology has played a much larger role than today in Germany, the objective of the research was to characterize strength and toughness in structural steels of NPP, i.e. after welding and stress relieve heat treatment. The actual techniques at that time were magnetic and acoustic Barkhausen noise measurements [5, 6], just – at that time - described in a larger NTIAC report by George Matzkanin [7]. Starting so, the institute of the author has further developed the technique and has especially forced the development of systems and equipments technology which today – with more than 100 industrial applications – is reliably implemented into practice for materials characterization, including residual stress measurements.

However, also here we have still open scientific questions, which ask for answers and the scientific community is working hard on it. On one hand, this is the application online and process-integrated in steel and machinery building industry, i.e., at high inspection speed; on the other hand, it is the characterization of ageing phenomena at components of the power generating industry, like plastic deformation, cyclic fatigue, creep, thermal, and neutron degradation.

2. MT for Defect Inspection

2.1 MPI – Machine Vision – Aided Analysis of Inspection Findings

Recently, Vetterlein [8] published a Ph.D. thesis on newly developed automated systems for MPI. The industrial application sector mainly is the automotive industry with mass part inspection asking for high put-through per shift and the fulfilling of zero-defect principles in quality management concerning the inspection reliability, i.e. a very low falsenegative rate in order to avoid pseudo scrap. With human beings as sensors in the process chain that requirement cannot be satisfactorily achieved. By fully automating the handling of the parts under inspection, the magnetization, the spraying of magnetic ink, the black-light illuminating, the optical pickup of the magnetic particle indications and the analysis of them by machine vision procedures like pattern segmentation and recognition the full process is controlled.

This includes also supervising procedures like control of the black-light intensity and/or the quality of the liquid powder suspension, i.e. rate of powder deterioration by separation of powder and the fluorescent color. Figure 1 shows drive shafts as typical automotive parts and Figure 2 gives a view on the MPI system components. Figure 3 documents the primary MP indications and Figure 4 the inspection result after machine vision application.

2.2 MT for Defect Inspection by GMR

In 1988, it was Grünberg [9] of theResearch Center in Jülich, Germany, observing the 'giant magnetic resistance effect', basing on quantum mechanical spin-coupling between two nm thick ferromagnetic sheets, separated by a nm thick Cu-layer. The electrical resistance of the Cu-layer, i.e. the scattering of conductive electrons, depends on the structure of the closer domains in the adherent ferromagnetic layers and therefore depends on the strength of external acting magnetic fields. Compared with other magnetic sensors, after the SQUID the GMR today are the most sensitive. In table 1 the data of both types of sensors are compared. The AMR sensors (Amorphous Magneto-Resistive effect) [10] are 10 times more sensitive than Hall-effect sensors and today are the most applied read-out sensors in hard disks. They will be replaced in the future by GMR because of the higher sensitivity allowing much higher data density for data storage. The reason for the low market prize is the hard disc application as well as the use in the audio field (mini disc of the Sony Corp.). The institute of the author, very early, started with GMR applications in NDT. The first was in steel industry [11] in order to detect non-metallic inclusions in steel strips, produced for deep drawing products like cans or packaging material. Figure 5 is presenting the micrograph of the smallest irregularities which were detected, a cloud of non-metallic inclusions in the size range of some 100 µm by sensing the magnetic flux leakage with a GMR-array and a probe lift-off of 2mm. The strip is magnetized into magnetic saturation and the GMR are from gradiometer type with the advantage to efficiently suppress ambient disturbing magnetic fields.

A further inspection task was in automotive industry to inspect pusher beams of rack steering gears. Here –after inductive hardening – hardening cracks in the tooth flanks can occur. Because of the geometry influences MPI is disturbed by high background fluorescent spurious indications. To overcome the problem a GMR solution was proposed using a gradiometer array. Figure 6 shows the inspection result in a gradiometer image where the crack indication of an axial crack with a signal/noise ratio of 27 dB is indicated. Figure 7 documents the sensitivity comparing MPI and GMR gradiometer imaging. The magnetization of the parts in this case is by current flow in the axial direction of the beam.

3. MT for Microstructure Characterization

3.1 Micromagntic NDT in a Steel Rolling Mill Application

In steel industry is – so far as possible – the strong request to online monitor the produced quality after each production step in terms of mechanical properties which characterize the fitness for use. Therefore the determination of properties like yield strength ($R_{p0.2}$), tensile strength (R_m) and deep drawing parameters (r_m, Δr) are of interest.

In European steel research [12] in the last years the potential of micromagnetic NDT was demonstrated by using the 3MA approach. 3MA (micromagnetic, multiparameter, microstrucure and stress analysis) is a combination technique based on magnetic Barkhausen noise measurements, incremental permeability measurements, the harmonic analysis of the tangential magnetic field and eddy current impedance measurements at 3 different frequencies. The redundant and divers information obtained by these NDT techniques [13] are data fused utilizing linear regression, pattern recognition or neural network algorithms to find a reliable model to predict the mechanical properties. There are many similarities between mechanical and magnetic properties of magnetic materials. Microstructure characteristics which are responsible for strengthening or softening materials like vacancies, dissolved atoms, dislocations, precipitates, and grain and phase boundaries influence the dislocation movement under mechanical loads similar as they hinder the Bloch wall movement under magnetic loads. The magnetic techniques combined in 3MA therefore are selected to collect information basing on irreversible and reversible micromagnetic elementary processes, i.e. the sensors in the material are the Bloch walls which in iron-based materials are only 90° and 180° Bloch walls. However the technology can be applied at ferromagnetic materials only.

The 3MA system in the last years was redesigned (hard- and software) and Figure 8 shows the hardware with the magnetic yoke transducer in combination with a laptop PC on which the 3MA-software is running. The communication is via Ethernet applying TCP-IP interface and protocol. Figure 9 is documenting an online inspection result obtained at cold rolled steel strips for car body design in a hot dip galvanizing line of ThyssenKrupp steel. Along the length of 2500m of the steel coil at a speed of up to 300m per minute, every 40cm the 3MA quantities are sensed of which by model calculation the elastic limit is predicted. Figure 10 shows the magnetic probe head which is integrated into carrier which automatically can drive in a roller table position. The strip is guided by 2 rolls under tension (coiler) with a lift-off of 2mm ± 1mm. Table 2 documents the results obtained inline and in comparison with destructive testing results discussing 4 different steel grades and the residual standard deviation absolute ad relative in % of the elastic limit. In general, the measuring inaccuracy is not far away from the destructive reference method.

It should be mentioned here that 3MA has also successfully demonstrated its ability to predict mechanical properties at hot rolled heavy steel plates. In this case a special remote controlled trolley was developed in which the 3MA system was integrated; Figure 11 shows this trolley in a measuring position on the plate.

3.2 3MA for Ageing Characterization

3MA is applied in the nuclear safety research program of the German minister of economy and technology in order to characterize ageing phenomena in steel members of piping and pressure vessels in the primary circuit of nuclear power plants.

As function of the exposition at enhanced temperatures (280-300°C) the Cu-rich (1.65 weight %) structural steel (WB36, 15 NiCuMoNb 5 – 1.6368) has the tendency for thermal ageing which is due to 1-2nm Cuparticles which precipitate. The particles are relevant obstacles and pinning points for dislocation movement resulting in remarkable degradation phenomena (ÄóY=+150MPa, dT41=+70°C).3MA has the ability to predict this degradation and measuring quantities basing on characterizing the Cu-state (in solid solution or in precipitates) as well as quantize which are sensitive to higher order residual stresses (the Cu particles are coherent (bcc lattice) in the matrix) are suitable for the characterization. Figure 12 documents on the left hand side the changes of the eddy current impedance (amplitude and phase) as function of the exposure time (simulation at 400°C) and on the right hand side the correlation analysis with 3MA taking into account Barkhausen noise, tangential field harmonics and eddy current impedance.

Fig. 1: Drive shafts

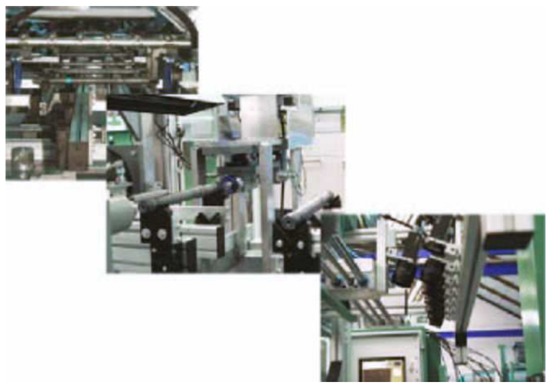

Fig. 2: Shaft transportation, inspection station, camera set-up for visualization

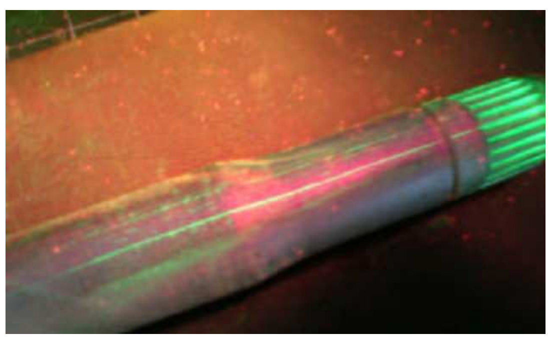

Fig. 3: Shaft under black-light

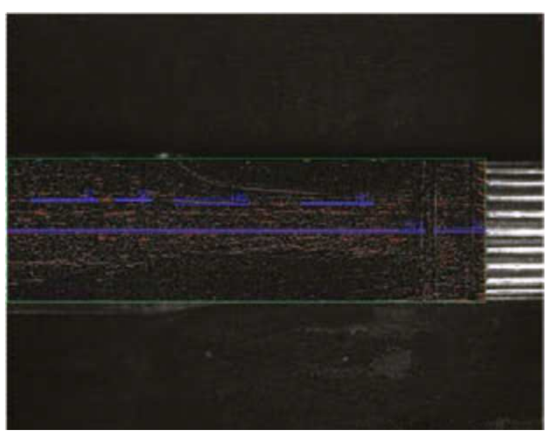

Fig. 4: Shaft image after machine vision

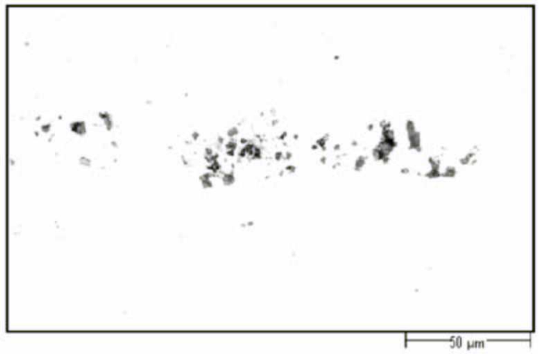

Fig. 5: Micrograph of non-metallic inclusions in a steel strip for deep drawing applications

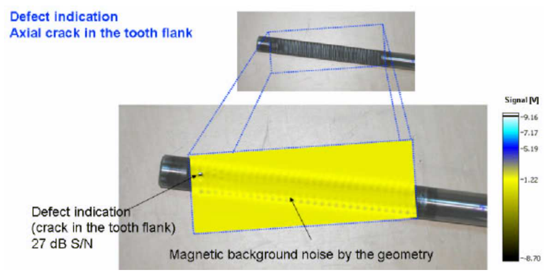

Fig. 6: Crack detection in a pusher beam tooth flank by a GMR gradiometer array

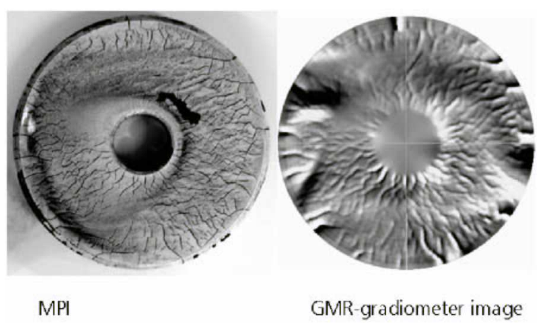

Fig. 7: MPI at a reference test specimen and the GMR gradiometer image

Fig. 8: 3MA system and transducer in combination with a laptop PC

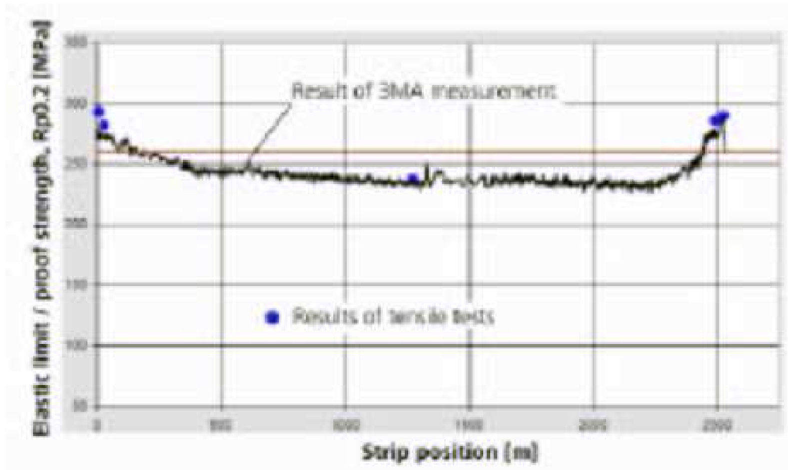

Fig. 9: Elastic limit predicted by 3MA at a steel strip

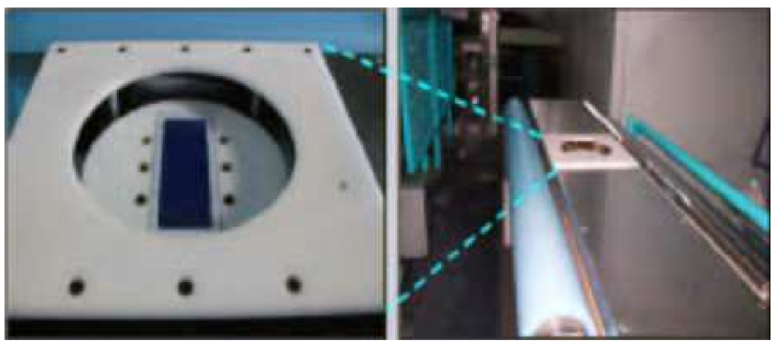

Fig. 10: Magnetic probe head and carrier integrated in a roller table position at ThyssenKrupp steel

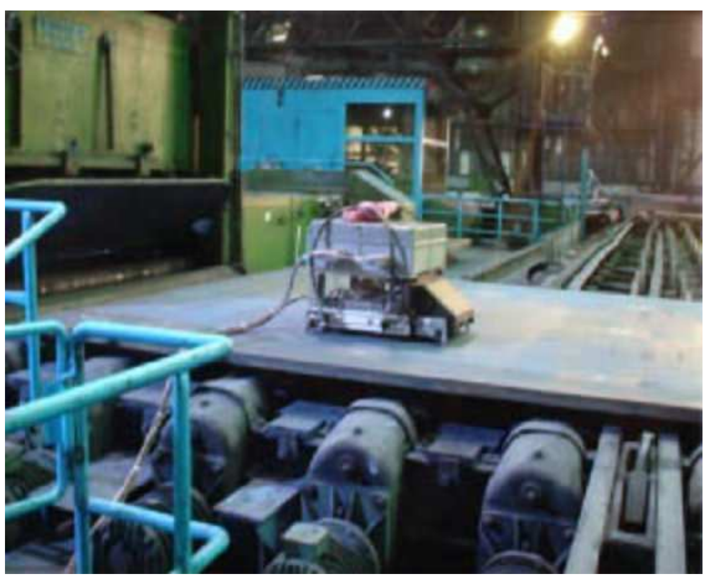

Fig. 11: Remote-controlled trolley with integrated 3MA-system in a measuring position on a heavy steel plate

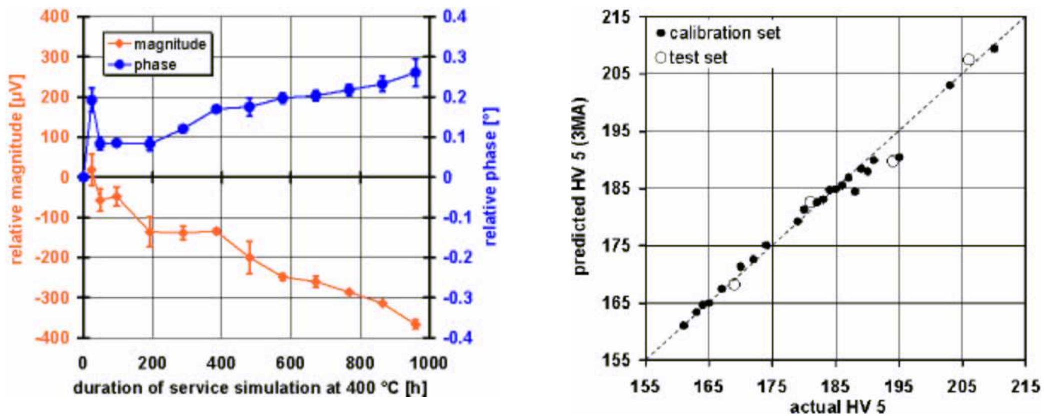

Fig. 12: 3MA for thermal ageing characterization in the structural steel 1.6368, eddy current impedance as function of exposition time (left) and 3MA regression analysis (right) predicting the hardness HV 5

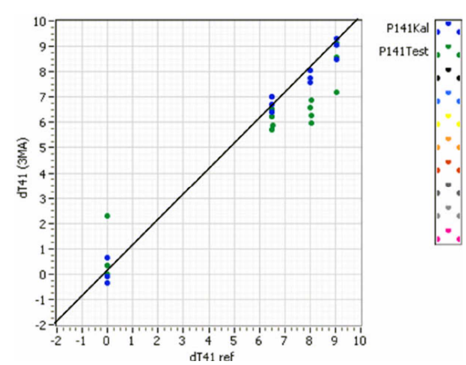

Fig. 13: 3MA approach predicting dT41 the change in the brittle to ductile transition temperature (compared with the non-irradiated material) and measured at a Charpy energy of 41J

Table 1: Sensitivity of magnetic field sensors

Sensitivity in Tesla/(Hz)$^{1/2}$	**AMR** 10^{-10} at room temperature	**GMR** 10^{-12}– 10^{-13}	**SQUID** (HTS) 10^{-12} at 77°K 10^{-14} at77°K in laboratory	**SQUID** (LTS) 10^{-15} at 4.2°K
Sensitivity in parts of the earth magnetic field	10^{-5}– 10^{-7}	10^{-7} – 10^{-8}	10^{-7} – 10^{-9}	10^{-10}

Table 2: 3MA compared with destructive test results

Steel class	**ΔRm (1σ) [MPa]**	**ΔRm (1σ) [%]**	**ΔRp0.2 (1σ) [MPa]**	**ΔRp0.2 (1σ) [%]**	**No. of strips**
IF	5.4	1.7	8.2	4.9	2667
IF, high strength	11.3	3.1	12.3	5.4	7764
Bake hardening	5.8	1.5	8.8	2.9	1294
Structural	7.9	2.5	10.1	5.1	164

A further ageing phenomenon of interest is neutron degradation. As compared with other countries in Germany the neutron fluence – according to the codes – is limited on 5×10^{18}n/cm^2(>1MeV) a special feasibility study was to document the potential of 3MA to characterize the microstructure changes due to neutron radiation. The material inspected in the hot cell was according the latest generation of German NPP (20 MnMoNi 5 5 optimized, base material and weld). The specimen some years ago were especially irradiated as Charpy specimen in a NPP. After performing the 3MA measurements, the Charpy tests were performed and the brittle-to-ductile transition temperature was determined. Then 3MA was calibrated in a regression analysis and with stochastically independent selected specimens the approach was tested. Figure 13 documents a result obtained at weld material of the optimized steel. A regression coefficient of 0.99 and a residual standard deviation of 0.35°C (calibration) respectively 1.2°C (test) can be obtained.

4. Conclusion

Magnetic testing by further developments in the last years has obtained a wider field of application in industry. The progress is in automation, reducing the human factor influences, in integration in production processes and enhancing lifetime and ageing management.

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